Fermilab

High Gradient Operations with 9mA Beam Loading

analyzing FLASH data from Sept. 09 test

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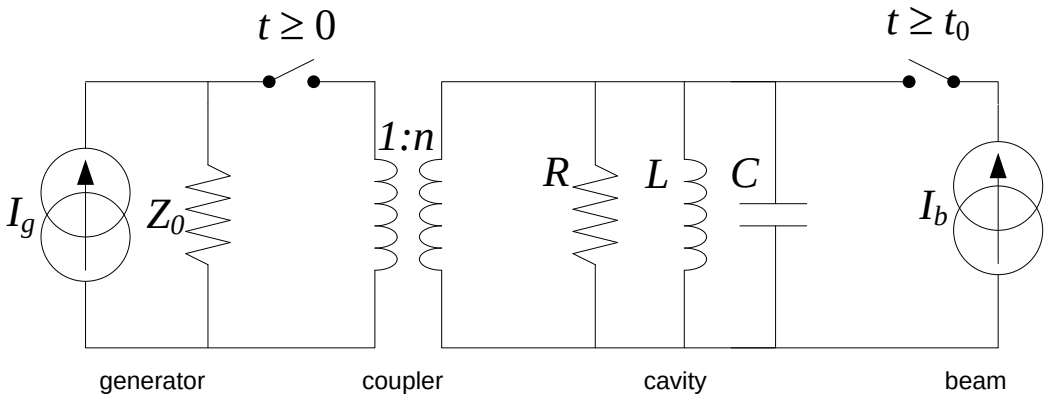
Workshop on Linac Operation with Long Bunch Trains – DESY – Feb. 22-24 2010

Outline

- Simulation tool
  - Model
  - Validation (comparison with experimental data)
- Review Sept. 2009 test
  - High beam data from DAQ
  - Tilts at high gradient
  - Avoid quenches by lowering gradients
- Moving forward
  - Suggested studies
  - Further simulation work
- What does this mean for ILC/XFEL ?
  - How critical is LFD ?
  - What (motorized) knobs ?

Simulation Model

Standard RLC cavity model:



Solving the RLC electrical model of a cavity → 2nd order differential equation *

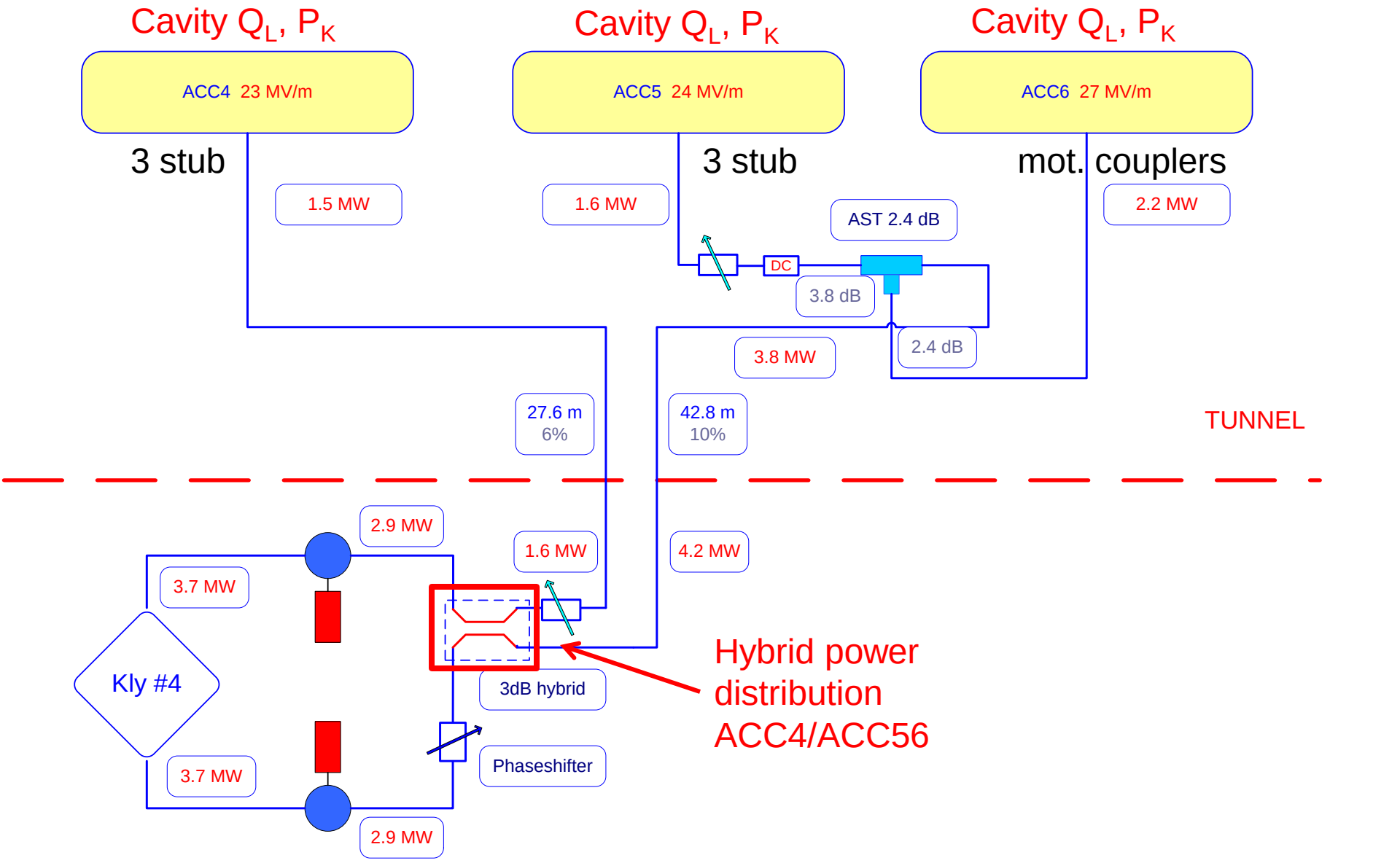
$$\ddot{\mathbf{V}}(t) + \frac{\omega_0}{Q_L}\dot{\mathbf{V}}(t) + \omega_0^2\mathbf{V}(t) = \frac{\omega_0 R_L}{Q_L}\dot{\mathbf{I}}(t)$$

1st order solution to the equation above:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} V_r \\ V_i \end{pmatrix} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} V_r \\ V_i \end{pmatrix} + \begin{pmatrix} R_L\omega_{1/2} & 0 \\ 0 & R_L\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} I_r \\ I_i \end{pmatrix}$$

* "Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities" , T. Schilcher PhD Thesis, 1998

Waveguide distribution for klystron #4 *(status 06.08.07)*



ACC4	21.8 MV/m			181 MeV			Max	191	Mev	Δ	10
Pin, MW	1.51		RF power	OK							
Qext	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0			
A, dB	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	not measured		
A (klystron)	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1			
Pcav, kW	169.7	169.7	169.7	169.7	169.7	169.7	169.7	169.7		1357.9	155
Ecav, MV/m	21.85	21.85	21.85	21.85	21.85	21.85	21.85	21.85		21.8	MV/m
I match	7.30	7.30	7.30	7.30	7.30	7.30	7.30	7.30			
Ecav, max	23	23	23	23	23	23	23	23		23.0	
	Cav 1	Cav 2	Cav 3	Cav 4	Cav 5	Cav 6	Cav 7	Cav 8			
Δφ	not measured									beam - forward RF	

setup from 08/24/2009

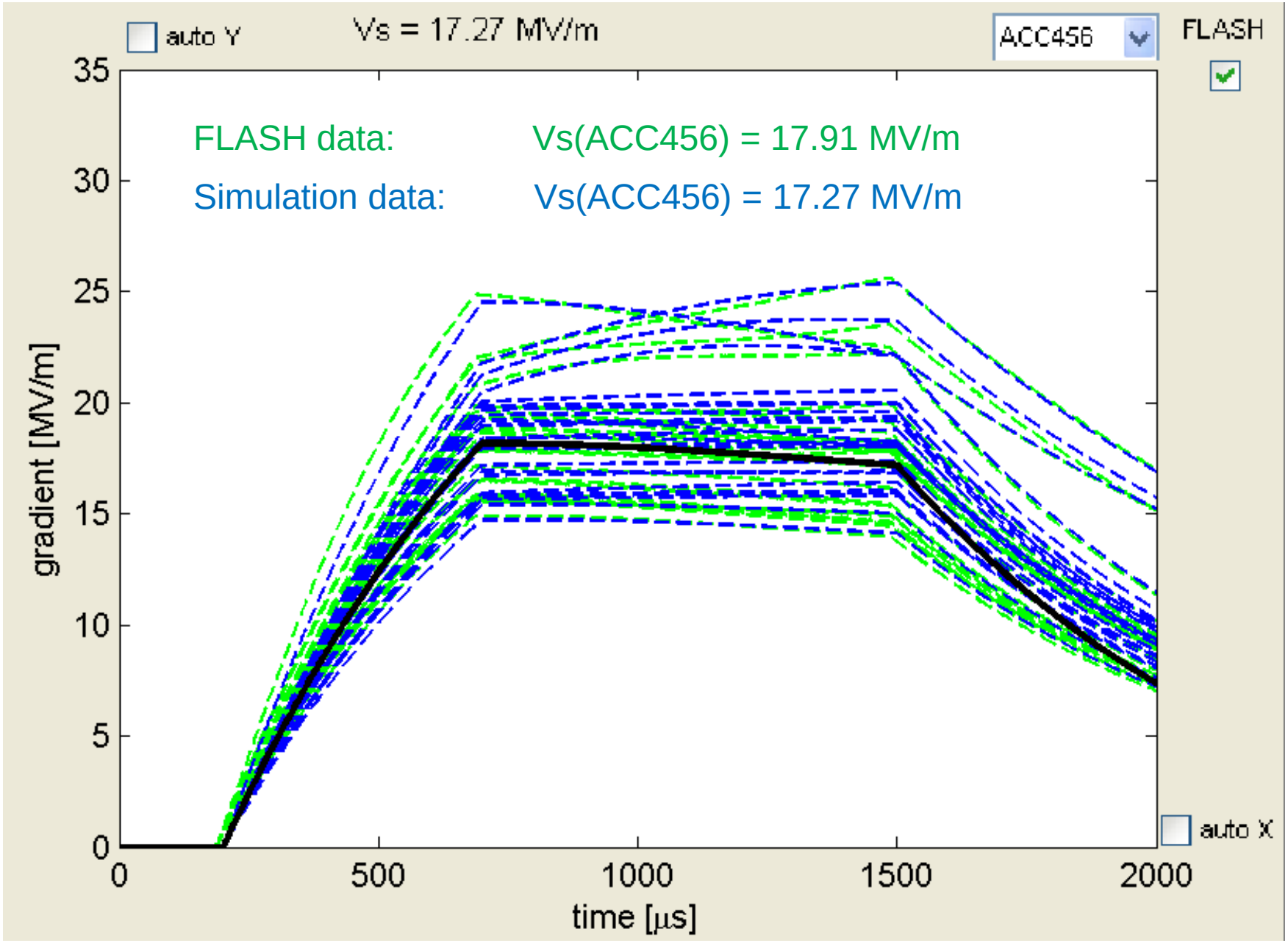
ACC4 cavities have motorized 3-stub

ACC5	22.6 MV/m			187 MeV			Max	231	Mev	Δ	44
Pin, MW	1.61		RF power	OK							
Qext	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0			
A, dB	9.67	9.64	9.61	9.53	9.34	9.35	9.38	9.39	measured		
A (klystron)	14.87	14.84	14.81	14.73	14.54	14.55	14.58	14.59			
Pcav, kW	173.5	174.7	175.9	179.2	187.2	186.8	185.5	185.1		1447.8	160
Ecav, MV/m	22.09	22.17	22.24	22.45	22.95	22.92	22.84	22.81		22.6	MV/m
I match	7.38	7.40	7.43	7.50	7.66	7.65	7.63	7.62			
Ecav, max	29	27	28	28	29	28	28	26		27.9	
	Cav 1	Cav 2	Cav 3	Cav 4	Cav 5	Cav 6	Cav 7	Cav 8			
Δφ	0	-6	11	1	15	6	6	20		beam - forward RF	

ACC5 cavities have motorized 3-stub tuners

ACC6	26.5 MV/m			220 MeV			Max	238	Mev	Δ	18
Pin, MW	2.18		RF power	OK							
Qext	2.95	2.97	3.00	2.98	3.00	2.98	2.99	2.98	11/21/2007		
A, dB	7.85	7.54	8.16	8.31	12.27	12.03	10.28	10.37	measured		
A, (klystron)	11.65	11.34	11.96	12.11	16.07	15.83	14.08	14.17			
Pcav, kW	357.6	384.0	332.9	321.6	129.2	136.6	204.3	200.2		2066.5	113
Ecav, MV/m	31.82	32.93	30.60	30.12	19.06	19.62	23.99	23.76		26.5	MV/m
I match	10.81	11.11	10.22	10.13	6.37	6.60	8.04	7.99			8.91
Ecav, max	34	32	34	32	21	21	29	26		28.6	
	Cav 1	Cav 2	Cav 3	Cav 4	Cav 5	Cav 6	Cav 7	Cav 8			
Δφ	0	0	0	0	0	0	0	0		beam - forward RF	

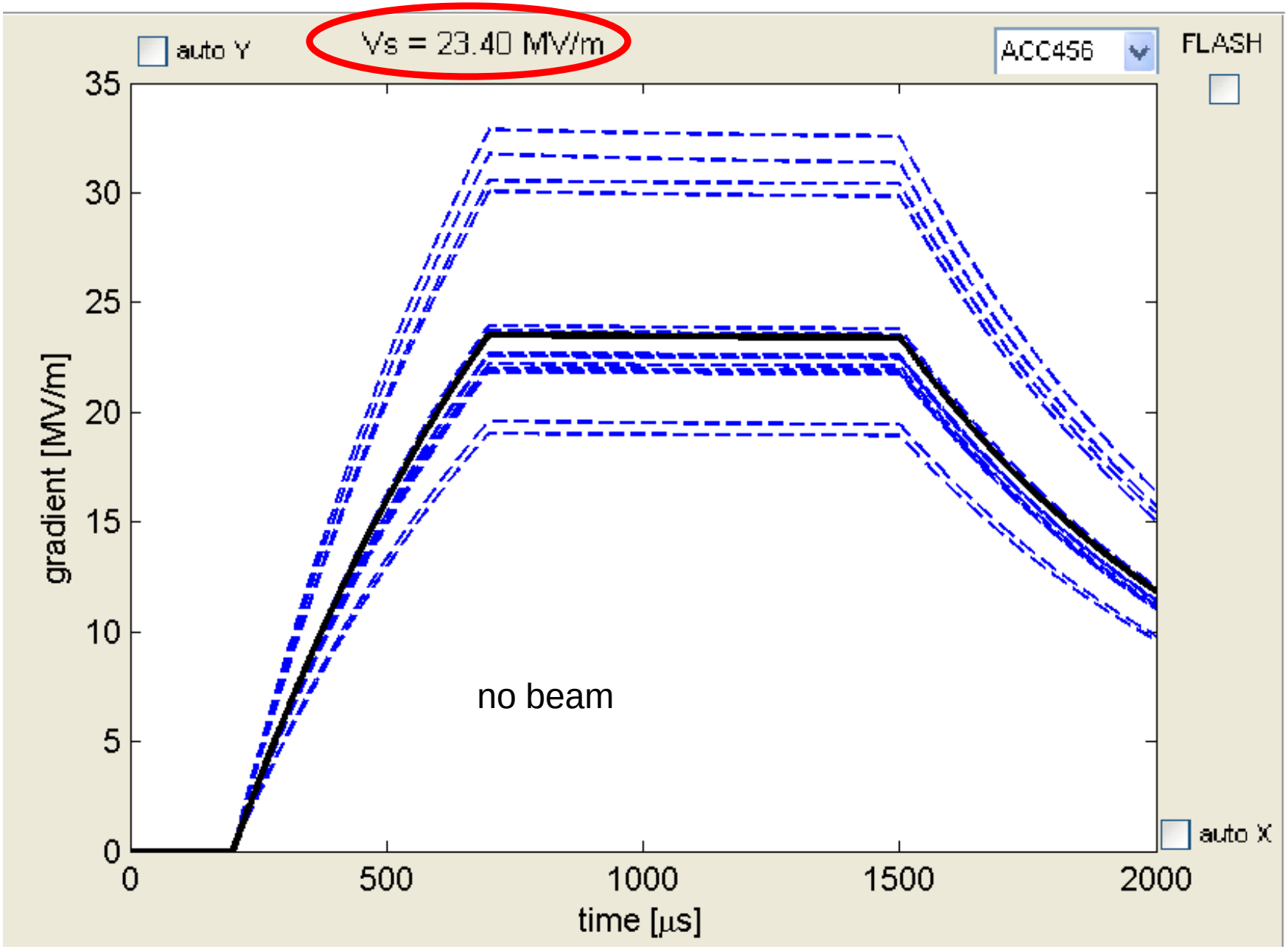
ACC6 cavities have motorized couplers and phase shifters



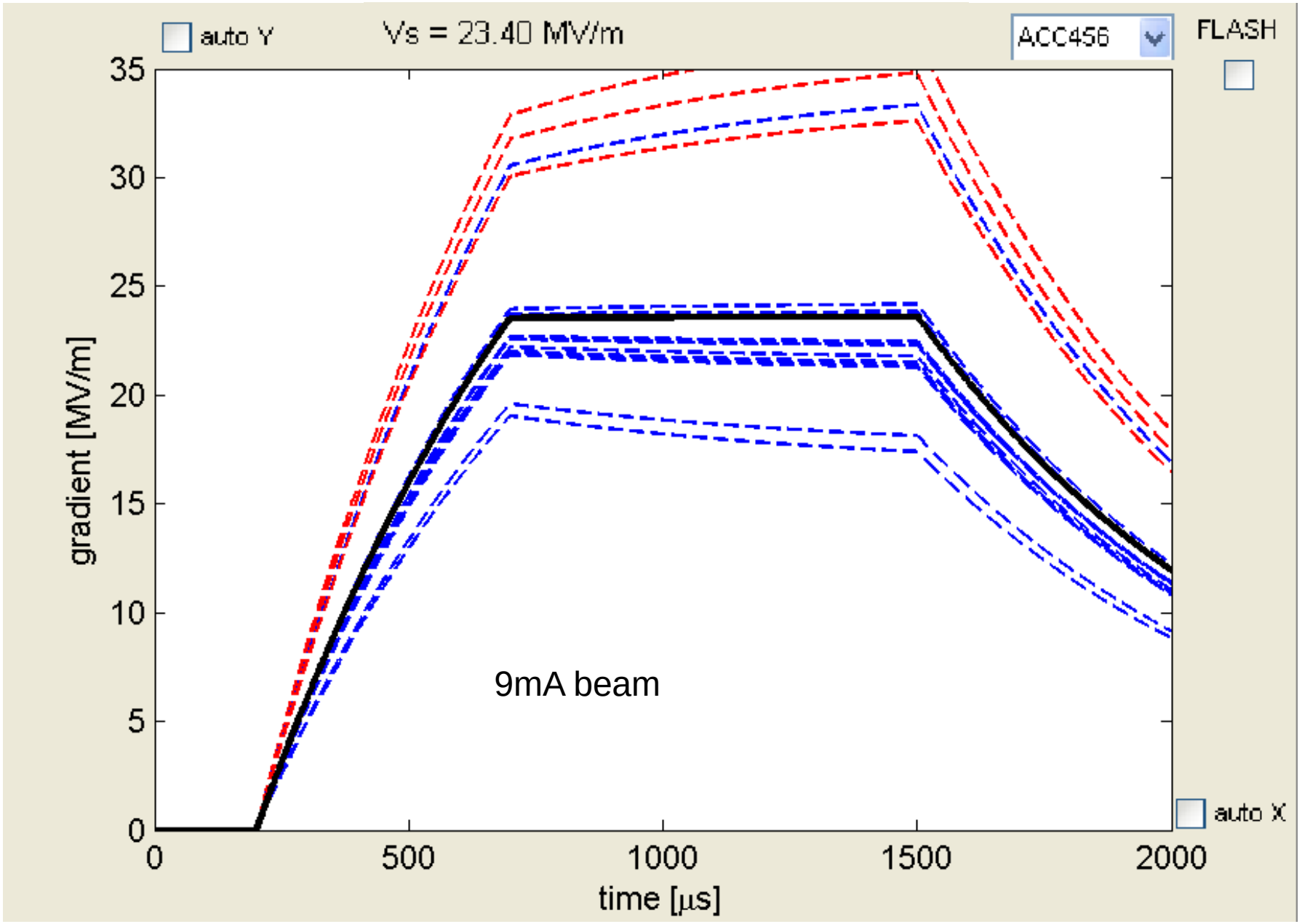
FLASH data from Aug. 27th 2009, 2:20 am

Review of Sept. 09 studies
(beam loading on high gradient cavities)

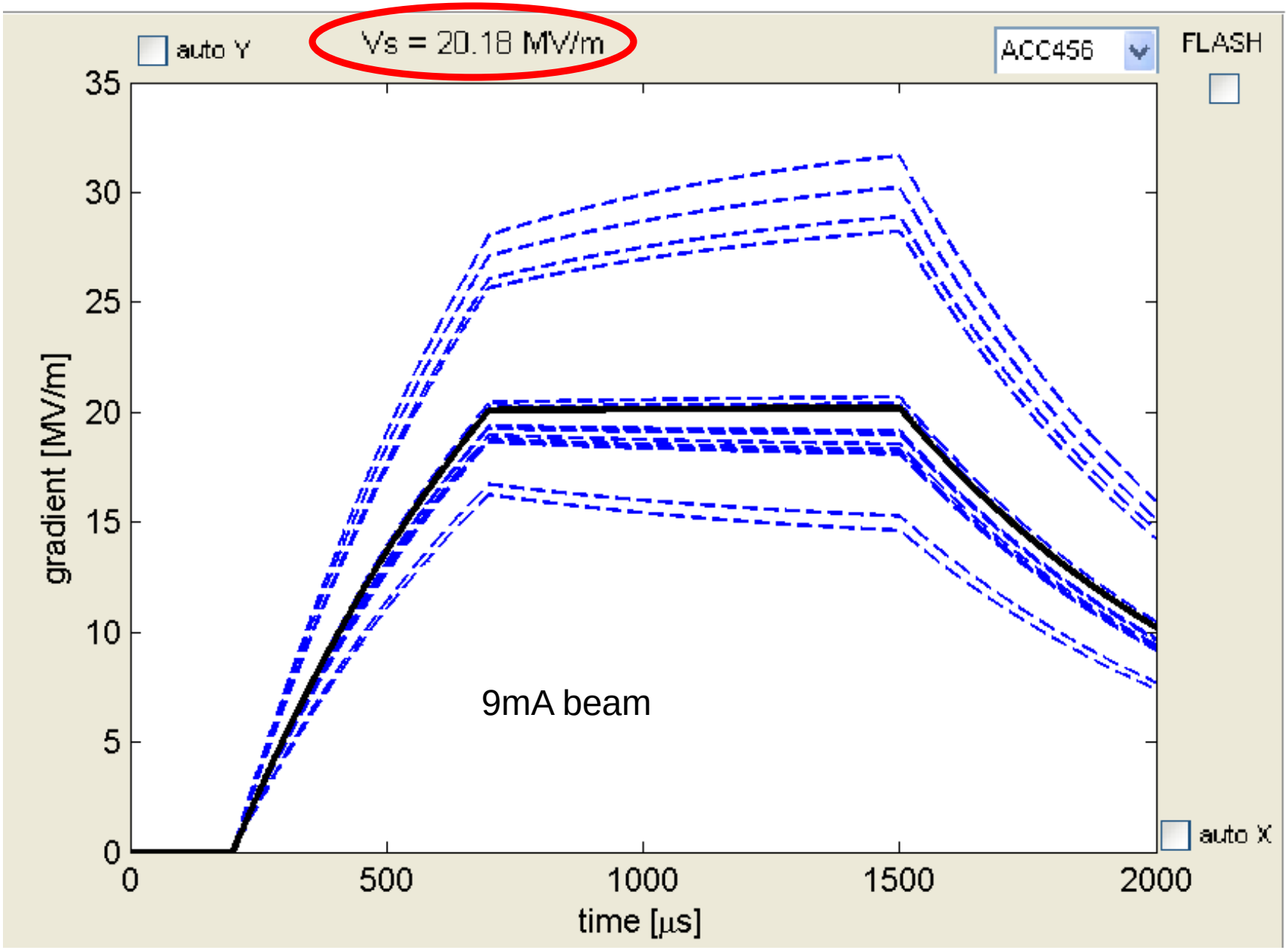
- Validated simulator (without beam)
  - Tuned to match FLASH ACC4, ACC5, and ACC6, according to setup from 08/24/2009 (Q_L's, P_K's)
  - Verified cavity gradients against experimental data
- Simulator predicts cavity quench for 9mA current for high gradient cavities
  - During Sept. test, gradient was lowered to prevent quenching
- Based on simulations, a solution is proposed to operate at higher gradient while preventing high gradient cavities to quench
  - Redistributing power among ACC4 and ACC56 (hybrid)
  - Adjusting QL for cavities 1-4 in ACC6 (not flat with zero beam)
  - The adjustments were tested without beam (Aug. 26 remote study) but not with beam

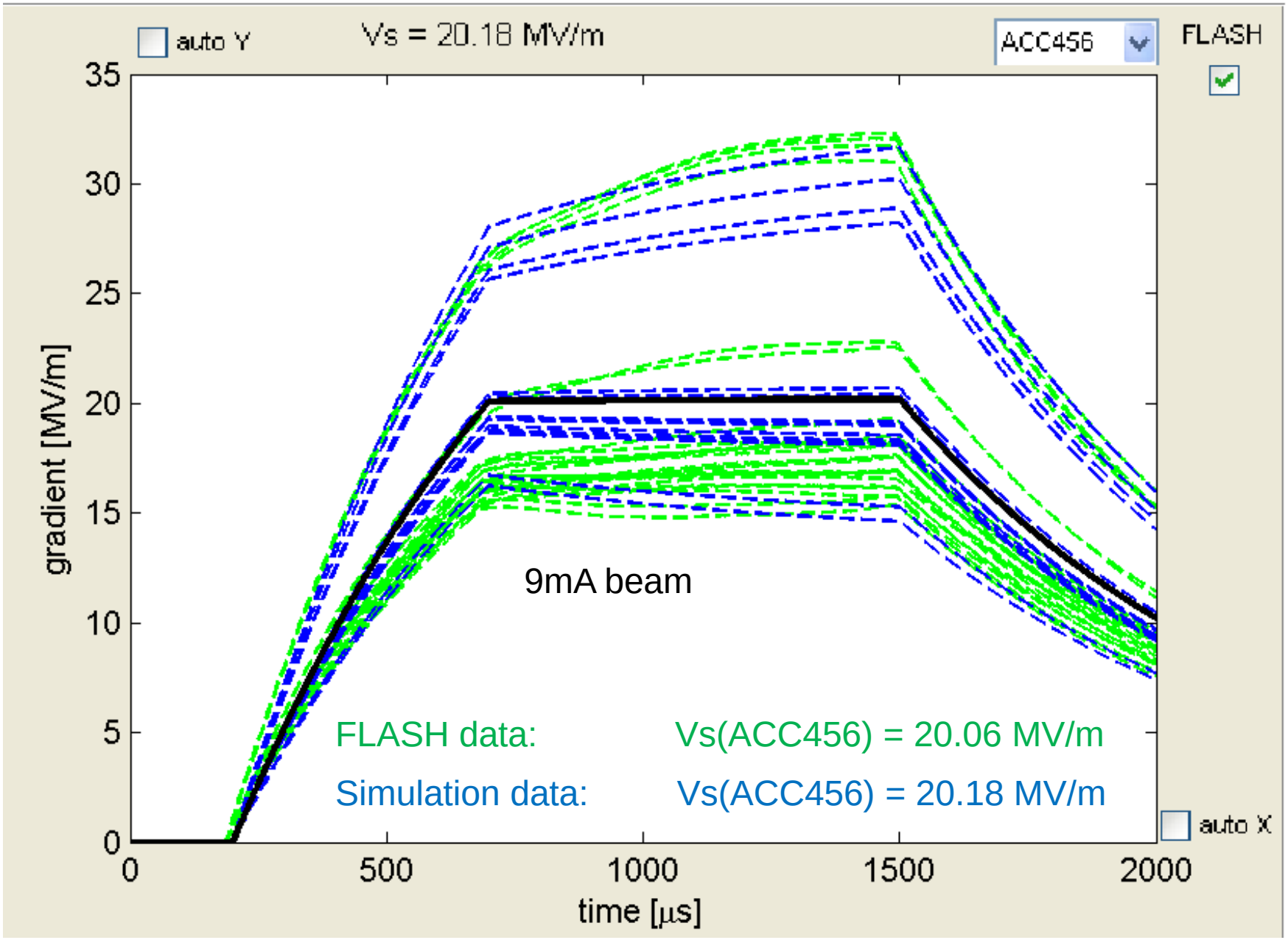


With Aug. 24th 2009 FLASH settings

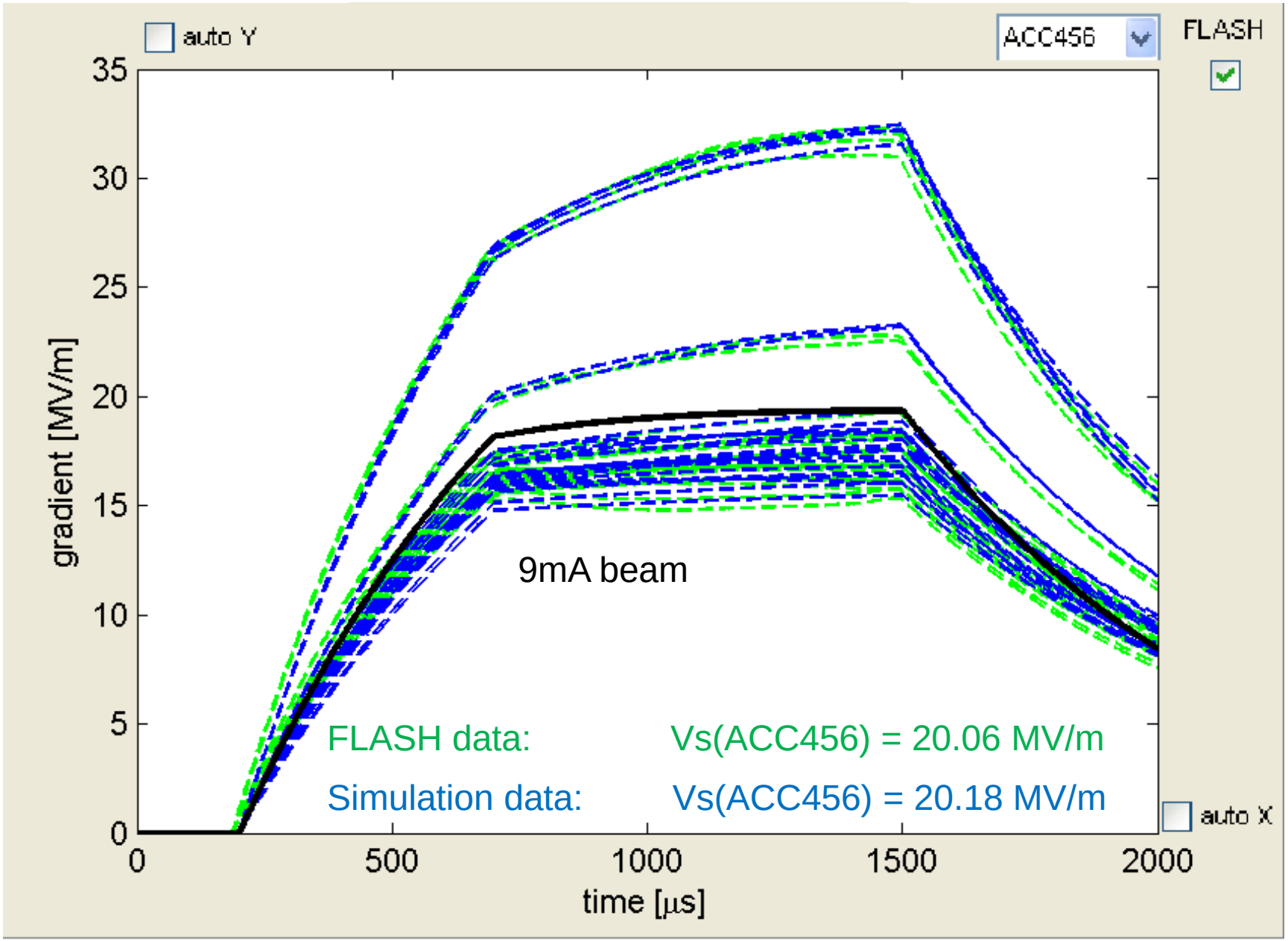


With Aug. 24th 2009 FLASH settings


auto Y
Vs = 20.18 MV/m
ACC456
FLASH
35
30
25
20
15
10
5
0
gradient [MV/m]
9mA beam
auto X
0
500
1000
1500
2000
time [µs]

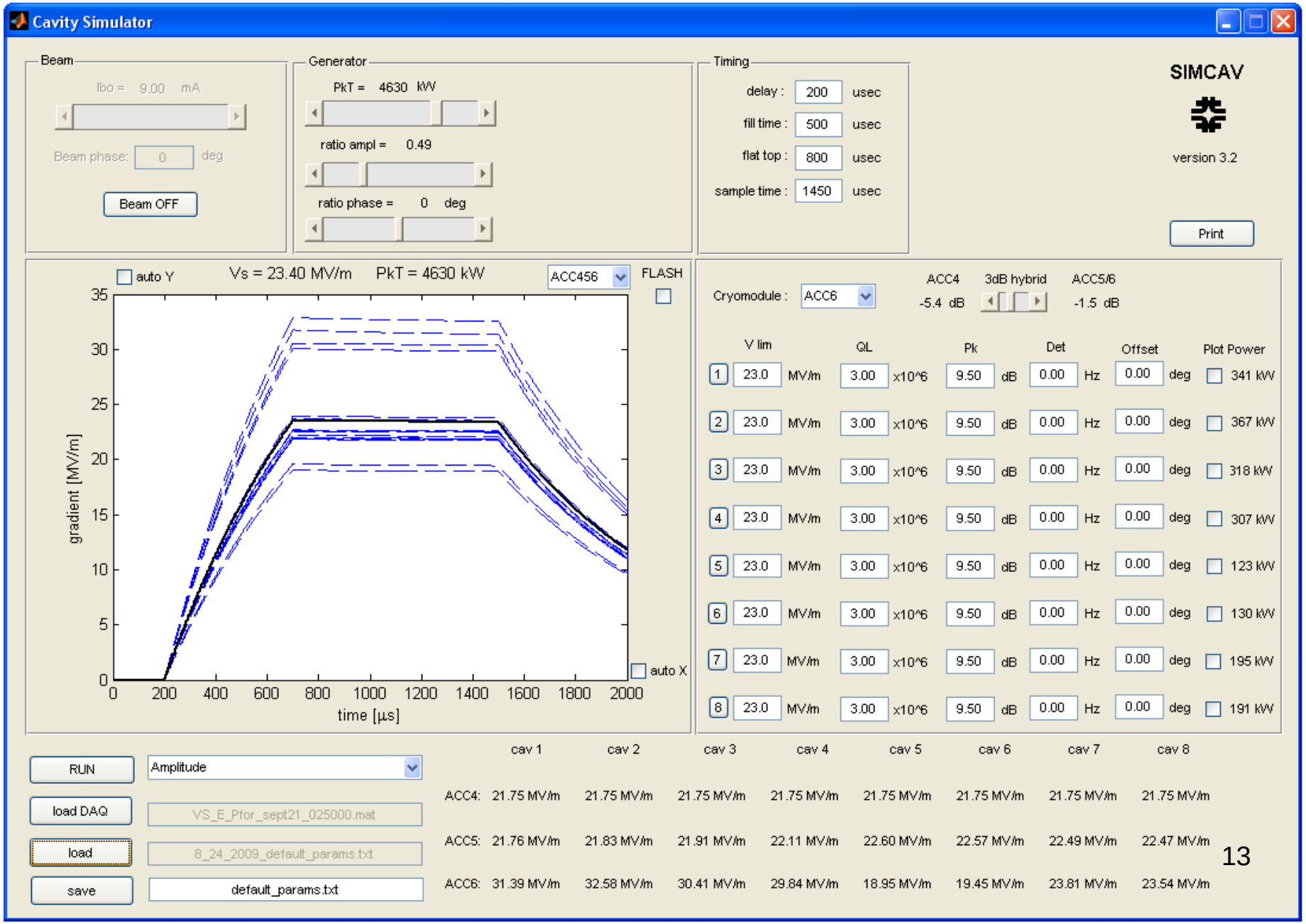


FLASH data from Sept. 21st 2009, 2:50 am



FLASH data from Sept. 21st 2009, 2:50 am

Proposed Studies



Moving forward

- Proposed studies
  - Rerun analysis with new RF distribution configuration for ACC4, 5, 6 and 7
  - Machine Test
- Study impact of cavity detuning
  - Roll over in gradient at the end of pulse
- Questions
  - 20 MV/m → 31.5 MV/m
  - How critical is LFD ?
  - What automatic knobs do we really need ?

Thank you!

Backup slides

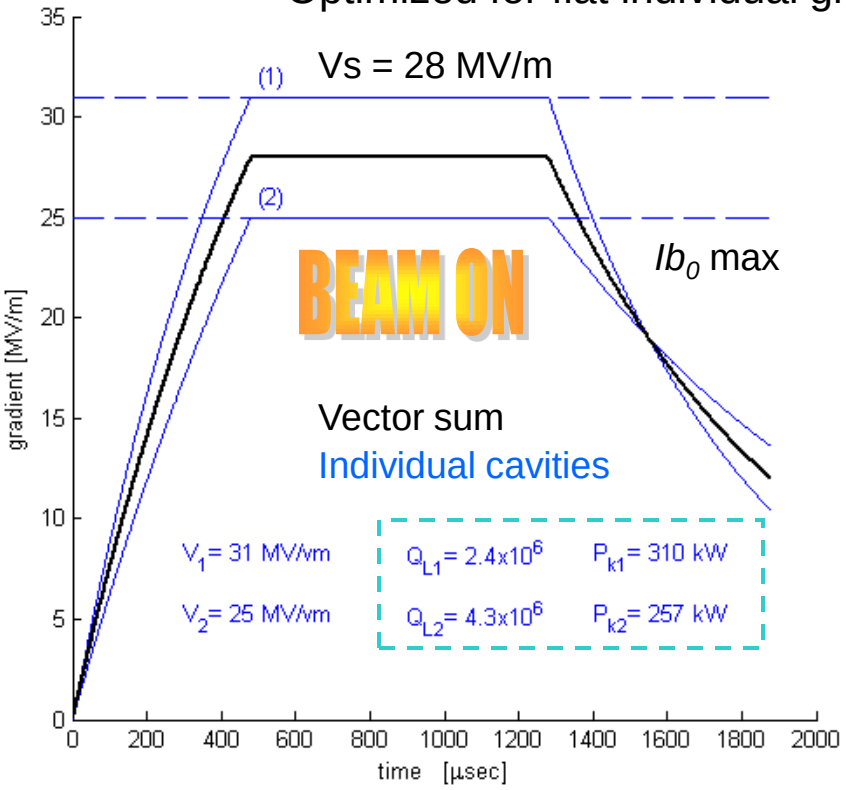
1st approach: individual Q_L, individual P_K

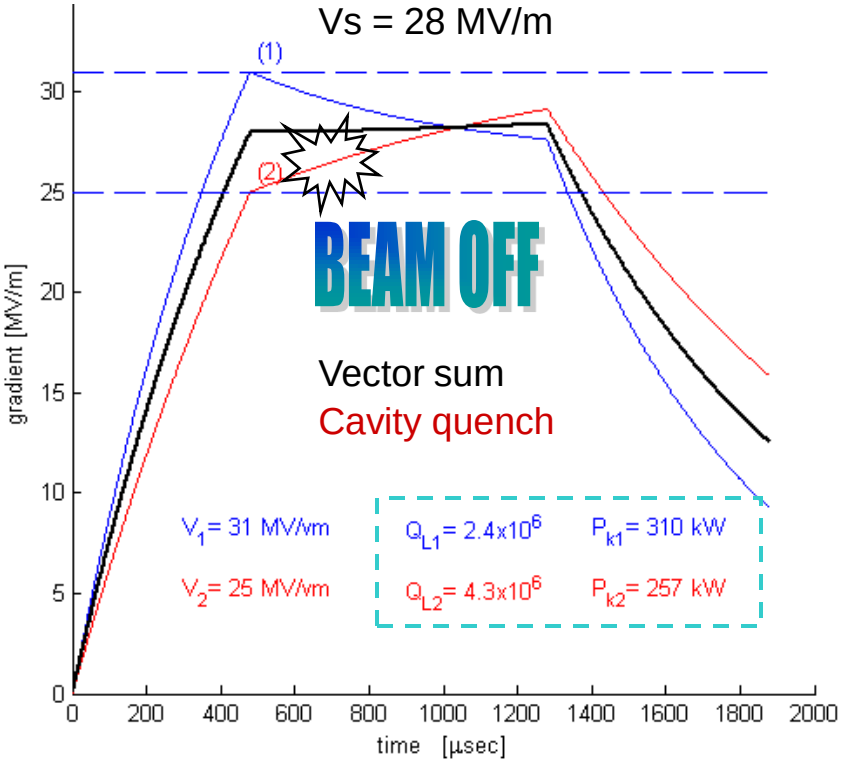
(optimized for max beam)

$$\frac{V}{V_0} = \frac{Q_L}{Q_{L0}}\left(2^{\frac{Q_{L0}}{Q_L}} - 1\right)$$

$$\frac{P_k}{P_{k0}} = \frac{Q_L}{Q_{L0}} 4^{\left(\frac{Q_{L0}}{Q_L} - 1\right)}$$

Optimized for flat individual gradient under maximum beam current





REFERENCE: *"RF distribution optimization in the main linac of the ILC"* K.Bane, C.Adolphsen, C.Nantista (PAC07)

2nd approach: same Q_L, individual P_K

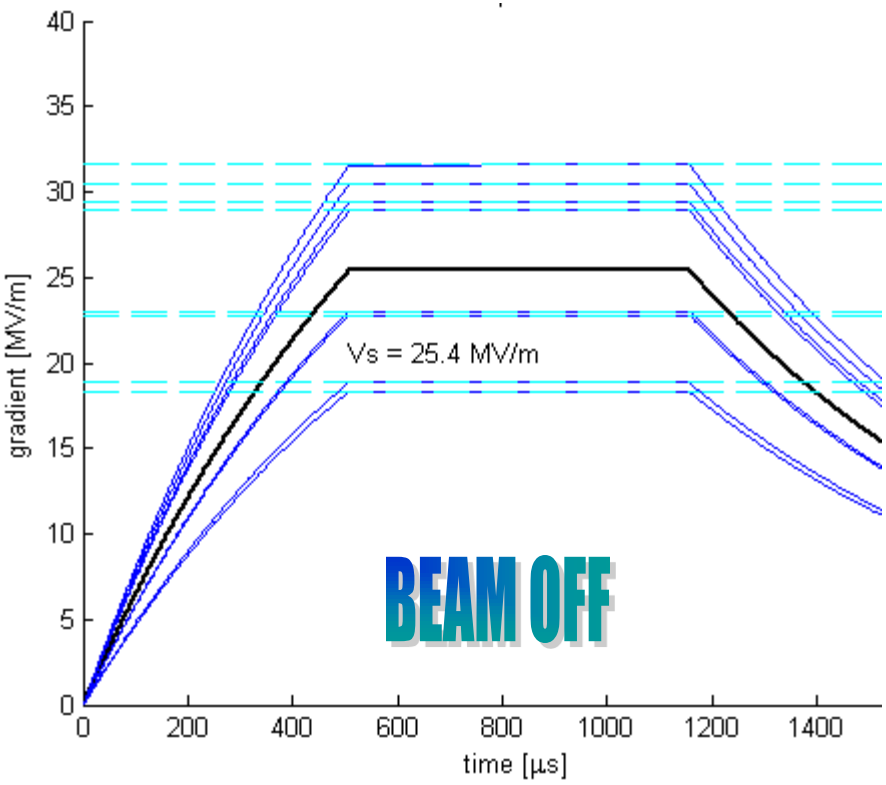
(optimized for no beam)

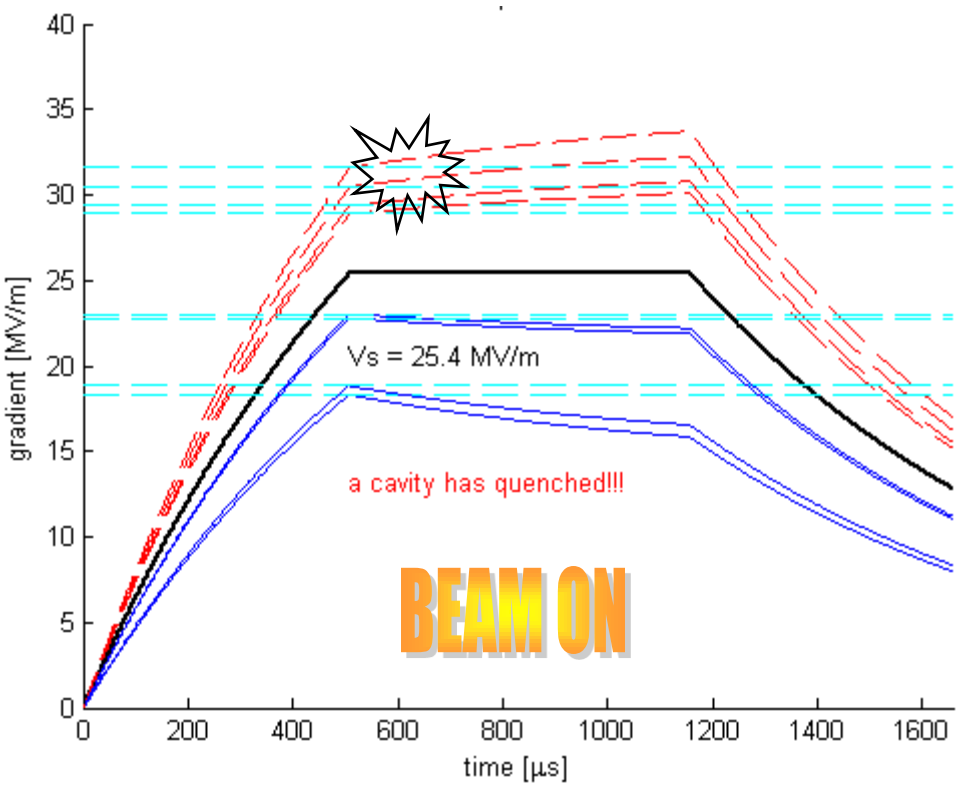
Same Q_L for all cavities (Q_L=3 x 10^6)

ACC6 : [30.48 31.59 29.41 28.91 18.32 18.84 23.04 22.80] MV/m

Ibo = 5 mA, beam pulse = 0.65 ms

Adjust power to set cavities at maximum gradient without beam

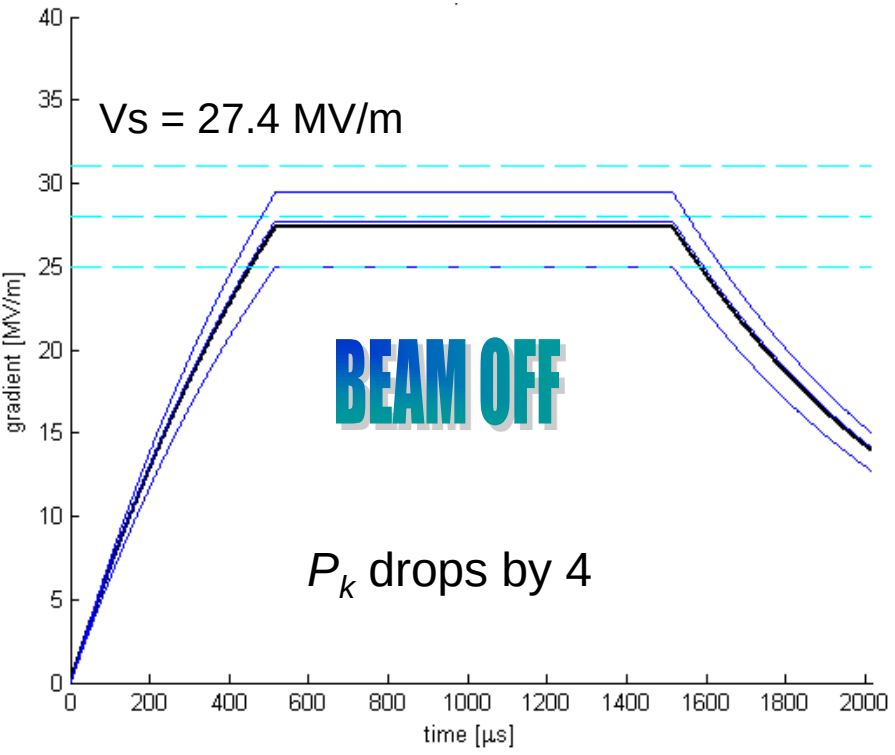


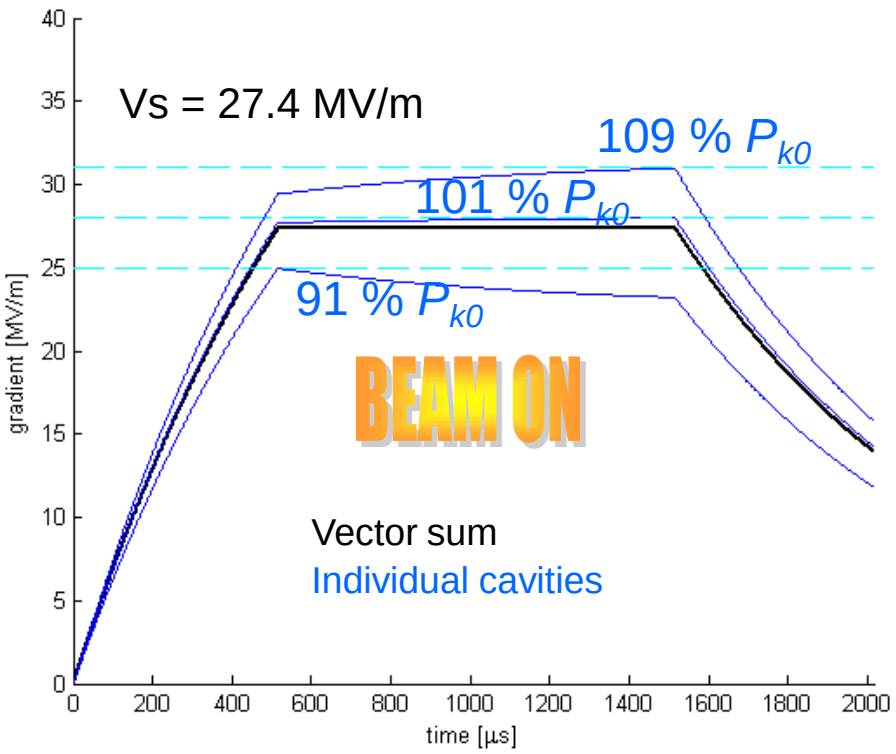


REFERENCE: *"XFEL waveguide distribution and more", V. Katalev,* XFEL HLRF kick off meeting, 2007

"Optimized": same Q_L, individual P_K

(optimized for any beam current)





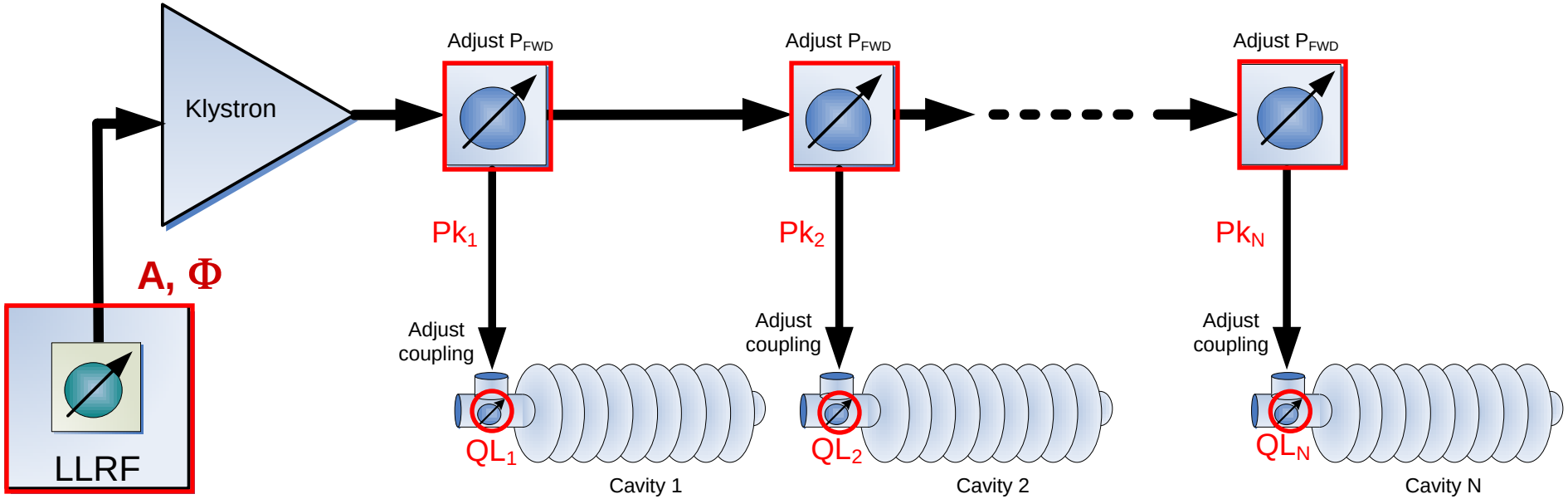
REFERENCE: *"Operational Solution to Obtaining a Flat Vector Sum from Multiple Cavities with Gradient Disparities",* J. Branlard, B. Chase, FNAL ILC DB doc # 490

Problem Statement

3 knobs: - LLRF

- cavity coupler

- waveguide power coupler



Example 1: FLASH 9mA test at DESY

"no-beam" study - 8/27/2009

Simulator mimics power distribution & coupling for ACC4, 5 and 6

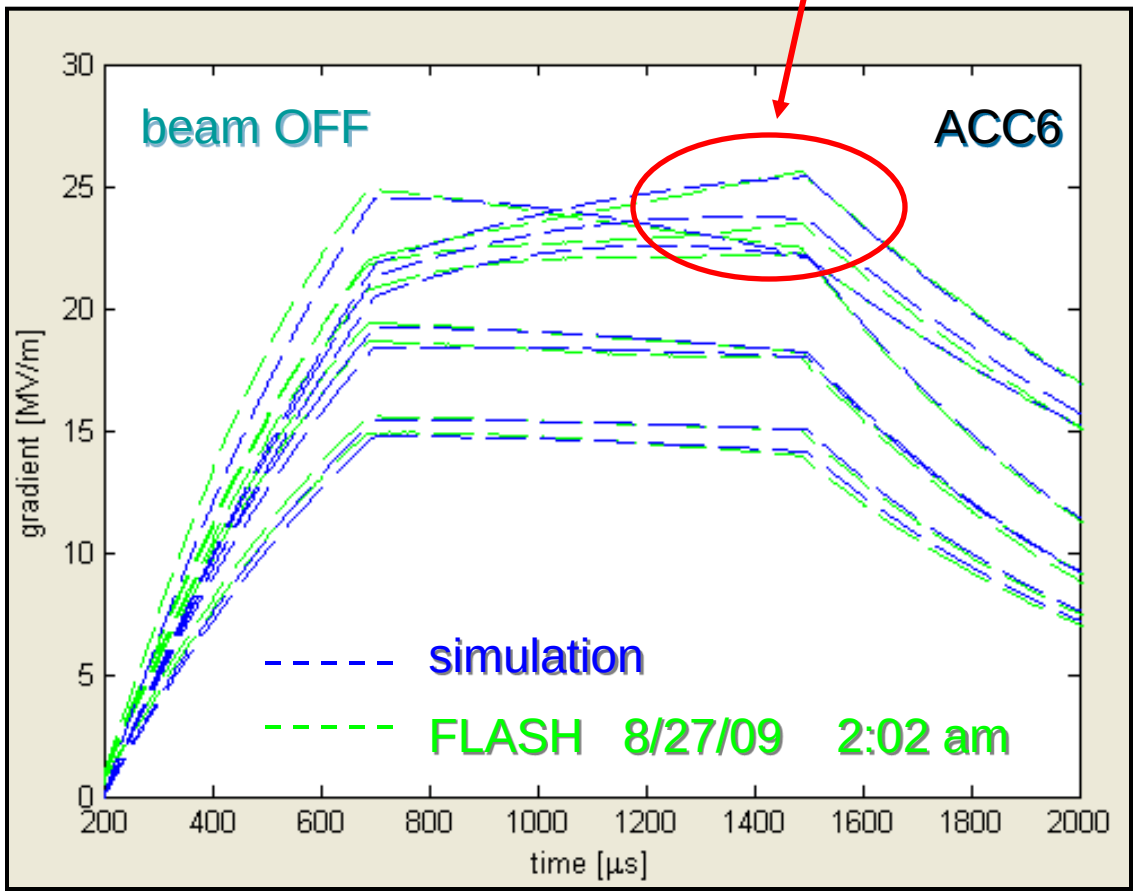
Verification of simulated cavity gradients vs. experimental data without beam

Using simulator, predict behavior with 9 mA beam current

Using simulator, propose tuning scheme to avoid quench of "high-gradient" cavities

Implement scheme and verify cavity tilts

cavities with adjusted coupler values



tilt up without beam → flat with beam

Example 1: FLASH 9mA test at DESY

"high beam" study - 9/21/2009

Verification of model against experimental data with 9mA beam

Could not implement optimized scheme with beam

→ lowered klystron power for safe operation

Validate simulator as useful tool for next test